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AUTHOR McConkie, George W.
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ABSTRACT

The application of computer technology to reading research has made it possible to study the perceptual processes that take place as people read with a level of precision never before attainable. This computer assisted research has revealed that where the eyes go for fixations is of significance to normal reading and that during each fixation only a word or two is being read. In addition, it has shown that when during the fixation a word is perceived the length of fixation varies, probably depending upon when the mind is ready to deal with that information. Eye movement research techniques are likely to be useful in studying higher mental processes occurring during reading and will probably be important in the future for diagnosing specific reading difficulties. (FL)

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CENTER FOR THE STUDY OF READING

Reading Education Report No. 34

STUDYING THE READER'S PERCEPTUAL PROCESSES BY COMPUTER

George W. McConkie

University of Illinois at Urbana-Champaign

May 1982

University of Illinois
at Urbana-Champaign
51 Gerty Drive
Champaign, Illinois 61820

Bolt Beranek and Newman Inc.
50 Moulton Street
Cambridge, Massachusetts 02238

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Abstract

This paper describes a new computerized approach to studying the perceptual processes occurring as people read. It appears that where the eyes go for fixations is of some significance to normal reading, and that during each fixation only a word or two is being read. When during the fixation a word is perceived varies, probably depending on when the mind is ready to deal with that information. Finally, the paper suggests that eye movement techniques are likely to be useful in studying higher mental processes occurring during reading, and will probably be important in the future for diagnosing specific reading difficulties.

Studying the Reader's Perceptual Processes by Computer

Reading has always been recognized as the first of the "three R's," and teaching people to read has been seen as a, if not the, primary responsibility of the educational system. Because of this, research investigating the reading process has been continuing since before the turn of the century. Many of the issues being studied today, especially those concerning the perceptual processes in reading, are dealt with in Huey's (1908) book, which contains many insightful observations about reading. It is not surprising that progress in understanding the mental processes involved in reading has been relatively slow, since reading is a complex mental activity which takes place rapidly and privately within a person's mind, making it difficult to study. It is not only unobservable to other people, but the readers themselves hardly know what they are doing. Readers have the experience of desiring to understand, of passing their eyes over the text, and, in the process, of gaining meaning and knowledge. Even though they may accurately comprehend the text, they are still quite unable to shed much light on just how they did it: what they were seeing, how frequently their eyes stopped, how they decided on the meaning of a word having more than one potential meaning, or how seeing a series of words

called a new, complex thought to mind. Decades of research on reading have only begun to give us an understanding of what the mind is doing as it carries out this remarkable activity.

Recently there has been a series of advancements in our understanding of perception in reading. The application of computer technology to reading research has made it possible to study the perceptual processes that are taking place as people read, with a level of precision that has never before been possible. The purpose of this paper is to describe some of this research, including the techniques being used to study perception in such detail, and some of the discoveries which have resulted. For a more detailed review, see McConkie (in press). First, however, it is necessary to recognize that, in reading, as in most visual tasks, perception occurs by means of a rapid series of eye movements, taking the eyes to different locations. Before discussing the nature of the perceptual processes it is necessary to describe some of the characteristics of these eye movements.

Eye Movements During Reading

As people read, they have the feeling that their eyes are moving most of the time. In reality, they are moving less than 10% of the time. About four times per second, on the average, the reader's eyes make quick movements, referred to as saccadic

eye movements, or saccades, which then center the eyes on some new location in the text. Depending on the lengths of the saccades, they can take from about 20 to 80 milliseconds (msec.), with a saccade of average length (8-10 letter positions) requiring about 35 msec. In making saccadic movements, the eyes can reach velocities up to 800 degrees of visual angle per second (Alpern, 1971). During the periods between these saccades, which are referred to as fixations, the eyes are relatively still, showing only very small drifts and tremors. Incidentally, although these movements are so small that they can only be observed with the most sophisticated equipment, they are critical to proper vision. Without them, people have the experience of having objects they are looking at fragment and disappear. The average fixation is typically about 250 msec, about 1/4 second. Such factors as reading ability, text difficulty and reading purpose can change these averages (saccade length and fixation period) somewhat. However, these changes are small in comparison to the variation that exists within the eye movement record of a single person reading a single passage.

There are several techniques presently used to monitor a reader's eye movements. In one, for instance, the reader's eyes are illuminated with infrared (invisible) light, and small photo cells are mounted about 1/4 inch from the eyes' surface to

measure the amount of this light being reflected. These photocells are aimed at the boundary between the iris and the sclera (the white part of the eye), one on each side of the iris, as shown in Figure 1. Since the sclera is whitish in color, it reflects more light than does the iris. Thus, as the eyes rotate to the right, more of the sclera falls within the field of view of one of the photo cells, thus increasing the light being reflected to that cell, while more of the iris falls within the field of view of the other photo cell, reducing the light being reflected to it. Thus, the relative amount of light reflected to the two photo cells can be used to obtain an indication of the rotational position of the eyes, or the direction of gaze. Other common techniques include taking pictures of the eye with a television camera, and having the computer analyze the image of the pupil, and the location of a highlight within the pupil region, to identify the direction of the eye. Finally, a very accurate indication of eye position can be obtained with highly sophisticated equipment which tracks reflections from the front surface and the back of the lens of the eye. While these techniques differ in their degree of accuracy, and the degree to which the head must be stabilized, none of them requires direct contact with the eyes, as other techniques have (for instance, requiring specially-made contact lenses which do not slip on the

surface of the eyes as normal lenses do). Further information on methods of monitoring eye movements has been reviewed by Young and Sheena (1975).

Insert Figure 1 about here.

The most basic form of data obtained from eye movement equipment is shown in Figure 2, which presents about 3/4 second of an eye movement record from one college student reading a passage. This figure shows the relative horizontal position of the eyes at each msec (each 1/1000 second). Time is represented along the x axis, with a vertical line of the grid occurring at each 1/10 second. Eye position on the line of text is represented along the y axis, with a horizontal line of the grid occurring each five letter position. The part of the line of text being read is also shown on the y axis. When the curve is flat, as at point A, the eyes are in a fixation. Here the eyes are centered between the e and l in myself. At point B, where the curve begins to rise, the eyes have begun to move to a new location, and at point C, about 21 msec later, the eyes have completed a saccade and are coming to rest for a new fixation, centered on the first l in resolutely. The eyes then remain at

that location for about 325 msec before beginning a new saccade at point D. Finally, at point E, the eyes begin a regressive movement, moving leftward back along the line to examine something which might have been seen earlier. This figure illustrates how the eyes remain in position during fixations, and also how the eyes speed up, then slow down as they travel to each new location. The hump at the end of each saccade is a period of time during which the eyes are settling into position for the new fixation, after having been subjected to tremendous forces exerted by the ocular muscles to pull them quickly to their new position.

Insert Figure 2 about here.

A second, and, in the study of reading, a more common, method of illustrating eye movement data is shown in Figure 3. In this figure, the text which the person was reading is shown. The reader's eyes stopped for fixations centered on those letters under which there is a numeral. The numerals, in turn, indicate the sequence in which the fixations occurred. Finally, under each numeral is a number indicating the number of msec the eye stayed at that location. From this figure, it can be seen that

the reader's first fixation was centered on the letter h in the word ship, and that this was a short fixation, lasting only 122 msec. Following this, the eyes moved further to the left for the second fixation, and remained there for a longer period of time. Such small regressions are common at the beginning of each line, as the eyes seem to be finding an appropriate initial position after having made the long movement from the end of the prior line of text. This fixation is then followed by a series of fixations, each further to the right along the line. However, it should be noted that fixation 5 is a regression, the eyes having briefly moved leftward again for some reason.

Insert Figure 3 about here.

There are several points that should be made about this figure. First, it is apparent that, while the average fixation duration for this subject was about 235 msec as she read this passage, in fact there is considerable variability from fixation to fixation as to how long the eyes remain in each location, ranging from 24 to 339 msec on just this one line. It seems likely that this variability is related to the nature of the mental processes that are required at each position in the text.

Second, it is also the case that the lengths of the saccades vary considerably. Again, while the reader's average for this passage was about 8 letter positions (where a letter occupies about 1/3 deg. of visual angle), the saccades actually range from 2 to 12 letter positions on this line alone. Thus, there seem to be moment to moment differences in how far the mind needs to send the eyes. Third, even relatively good college-level readers fixate over half the words in a passage when they are reading carefully (Hogaboam & McConkie, 1981). Finally, whereas the eye movement record indicates with considerable precision (within less than 1 letter position, in this record) just where the eyes were centered during a fixation, and how long the eyes remained at that location, it does not indicate, by itself, what was being seen during that fixation. For example, while fixation 9 was centered directly on the word Saint, we do not know whether that word was seen on that fixation, and if so, whether it was the only word seen on that fixation. It is quite conceivable, for instance, that this word was seen on two or more of the fixations. This, then, takes us into questions about the nature of perception during reading.

Perception During Reading

It has long been known that people can see most precisely

that which they look at directly. Looking directly at a small object causes the eyes to rotate to a position where its image lies on the part of the retina known as the fovea, the region which has the greatest density of visual receptors and where the smallest details can be seen. Thus, what is seen during a fixation depends on three things: (a) where the eyes are centered during that fixation, (b) what the visual region is within which stimuli of interest can be resolved or seen, and (c) what the person attends to, during that fixation. Even though a person may direct his gaze toward a particular pattern, and its image may lie on the retina at a location where it could be seen, the person may fail to attend to it and thus fail to see it. In studying perception in reading, then, we must investigate where it is that the mind chooses to send the eyes for fixations, what region is typically seen during a fixation, and what is attended within that region. These will be referred to respectively as the eye movement control issue, the perceptual span issue, and the issue of attention to the text during a fixation. Finally, we must consider how the mind integrates the information it receives on successive fixations.

It should be noted that most of the research to be described has been done with relatively skilled readers, and not with children or disabled readers. Thus, the extension of this

research to studying the behavior of younger readers is needed before statements can be made about changes in the mental processes that are occurring as reading skill develops.

Eye Movement Control

It seems clear that during reading the mind is, at least much of the time, sending the eyes to rather precise locations in the text. If the eyes do not go to the specific locations to which they were sent, changes are observed in the eye movement pattern. This fact has been established in studies in which people read text from a computer display (Cathode-ray tube, or CRT) as their eye movements are being monitored (McConkie, Zola, & Wolverton, Note 1; O'Regan, 1981). These studies used an experimental technique in which the entire line of text was shifted two letter positions to right or left on the CRT during certain saccades while the eyes were moving. When the eyes stopped for the next fixation, they were directed toward a text position that was two letter positions away from where they normally would have been in the text under normal conditions. This is illustrated in Figure 4, which presents a line of text as it may have appeared during one fixation, with the eyes being centered on the letter marked by A. The location to which the eyes were sent on the next fixation is marked by a B. However,

during the eye movement, the text was moved, as shown in line 2 of the figure. Now the C indicates the location in the text where the eyes were actually centered during the next fixation, two letter positions away from where they normally would have been centered. Shifting the text in this manner causes a misplacement of the eyes in the text. When this happens, readers are totally unaware that the text has been moved, but their eye movements are definitely affected. A large number of short saccades occur, taking the eyes closer to the location where they would have been had the text not been moved. Thus, displacing the location of a fixation just two letter positions seems to have an effect on the perceptual system which leads to changes in the eye movement pattern, though this is not something of which the reader is conscious. There seems to be some good reason why the eyes are being sent to the exact location at which they are aimed in a saccade.

Insert Figure 4 about here.

Given that we know the eyes are being rather precisely controlled, then, we would like to know the rules the mind uses in determining where to send the eyes and how long to leave them

at each location. While we are far from having the full answer to this question, a few facts have become apparent. First, there is a tendency for the eyes to be sent to the centers of words (O'Regan, 1981; Rayner, 1979; Zola, 1981), and to avoid such less informative areas as blank areas (Abrams & Zuber, 1972-73) and the region between sentences (Rayner, 1975). There is evidence that the word "the" tends not to be fixated as frequently as other three-letter words (O'Regan, 1979; Rayner, 1977) though highly predictable longer words received just as many fixations as less predictable words (Zola, 1981). How long the eyes remain in a fixation is related to characteristics of the word on which it is centered, with more unusual words causing longer fixations (Rayner, 1977; Kliegl, Olson, & Davidson, Note 2) and with more highly constrained words receiving shorter fixations (Zola, 1981). Fixations also tend to be longer on words containing spelling errors (Zola, 1981), and on words in regions of the text that are regarded as being more important (Shebilske & Fisher, Note 3).

The important message here is that it appears that the eyes are responding sensitively to the mental processes of the reader. The language processes involved in comprehending the message of the text require information from the visual system. The visual system, in turn, must ensure that the eyes are appropriately

centered to provide this information when it is needed. A full description of how the eyes are moved in reading will probably require a description of the language comprehension processes, of how they depend on visual information from the text, and on how the perceptual system controls the eyes in response to the need for this information. Observing an aberrant eye movement pattern produced by a person with reading disabilities indicates that the flow of processing is not proceeding fluently as it does in better readers, but does not at present indicate the nature of the problem. It is quite likely that a strange pattern is reflecting the fact that problems are being encountered in comprehending the text, to which the reader must respond by doing further analysis and reanalysis of the text, thus requiring an unusual pattern of encountering the visual stimulus. It certainly is not necessarily the case that there is any problem with the reader's perceptual abilities or his ability to control his eyes, though among a few disabled readers this may be a problem (Elterman, Abel, Daroff, Dell'Osso, & Bornstein, 1980; Pavlidis, 1981; Pirozzolo & Rayner, 1978; Zangwill & Blakemore, 1972).

The Perceptual Span

When the eyes stop for a fixation, what region of text is

being seen? Does the reader see only a word or two, or is an entire phrase or clause being seen? Or does this depend on the level of a person's reading skill? These are critical questions in understanding reading and recent research is providing some relatively clear answers. Skilled readers utilize visual information no further than 4 letter positions to the left of the letter at the center of vision (McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980), and they do not appear to identify letters more than about 4-8 letter positions to the right (Underwood & McConkie, Note 4). Word length information may be perceived slightly further to the right than this (McConkie & Rayner, 1975; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

These conclusions have come from studies in which the text displayed on a CRT, is changed in specific ways as people read from it. For instance, if on certain fixations all letters outside this region are replaced by other letters, as shown in Figure 5, this does not produce any disruption in the normal reading process (Underwood & McConkie, Note 4).

Insert Figure 5 about here.

Another technique makes it possible to specify exactly the fixation on which a given letter was acquired. In this technique the experimenter identifies pairs of words that differ by a single letter, then writes a sentence into which either of the two words fits appropriately, as shown in Figure 6. As the person reads the sentence from the CRT, each time a saccade is made the critical letter is changed. Thus, the critical word changes from one fixation to the next, as the person reads. It is of interest that people are not aware that the word is changing, and that there is no evidence from the eye movement patterns that this manipulation has any effect on their reading. Thus, it appears that words are usually identified only on a single fixation, unless there is a later regression back to the word and it is examined again. After a person has read such a sentence, he indicates which of several words he saw in the sentence. Knowing which word the reader saw allows the experimenter to identify which fixation was the one on which the critical letter was seen (McConkie, Note 5). Initial studies using this technique indicate that readers are attending to the text in word-units. That is, whether a letter lying 2 letter positions to the left of the fixation point is seen on that fixation or not depends on whether it is in the word fixated or not (Rayner, Well, & Pollatsek, 1980).

Insert Figure 6 about here.

The picture that is emerging from these studies is that the skilled reader, at least when reading carefully, is encountering the text almost a word at a time. It is not true that phrases or larger units are being perceived at once, as some have suggested. Nor does it appear to be true that increasing reading skill broadens the region seen during a fixation. When 5th graders reading at the 3rd grade level are compared to other 5th graders reading at or above grade level, and to skilled college readers, no differences are observed in their perceptual spans, the region from which they acquire and use visual information during a fixation (Underwood, Note 6). These studies have also demonstrated that during a fixation people do not identify all the words that are within the visual region where they could be seen. Once a word is read on one fixation, for instance, even though it may lie at a retinal region on the next fixation that would allow it to be read once again, it appears not to be seen. For instance, if a word is read during one fixation, the fact that the word is changed for the next fixation is not noticed by the reader. Thus, in reading, as in other situations, we see only what we attend to, and learning to read must involve

learning to attend to the words at the right time and in the right way. This theme leads to the next issue.

Attending to the Text During a Fixation

It has been proposed that an efficient reader is one who develops the ability to use his knowledge of the language to reduce the degree to which he must do a visual analysis of the text. This proposal amounts to the suggestion that the reader can avoid attending to many aspects of the text which he can predict from his knowledge of the language (Goodman, 1976). However, a recent careful test of this hypothesis has failed to provide evidence for it (Zola, 1981).

In this study, nouns were identified which could be highly constrained by preceding them with some particular adjective. For instance, when given a passage about a football game indicating that a player sustained a "compound _____," nearly all readers predict that the next word will be fracture. However, if "compound" is replaced by "serious," few if any readers predict that the next word will be "fracture." Thus, by manipulating a single preceding adjective, the following word can be very highly constrained, or constrained to a much lower degree. The question investigated was whether constraining the word would change what information was used in perceiving it. In

the high constraint condition, common notions of reading would suggest that a skilled reader would hardly need to even look at the word.

The study yielded three important results. First, it found that making the word highly predictable did not cause people to fixate on the word less often. Thus, they did not skip over it when it was highly constrained, as might be expected. Second, when spelling errors were placed in the word (which should be missed if little visual analysis of the word was performed) they had just as much effect under the high constraint as under the low constraint condition. Apparently constraint was having very little effect on the degree to which the word was being perceived. Third, fixations on the word were slightly longer when it was less constrained. Apparently it took the mind slightly less time (in the neighborhood of .02 sec) to perceive and assimilate the meaning of the word when it was highly constrained by the preceding language. However, from the other findings, this did not seem to be because of any tendency to skip either the word or letters in it.

Present research provides little evidence that more highly skilled readers depend less on visual information from the text. There are recent suggestions that the truth may be just the

opposite; that greater reading skill allows one to depend more heavily on the visual information in reading, in the process of identifying the words (Frederiksen, Note 7; Stanovich, 1981). Of course, prior knowledge is very important for comprehending the message of the text.

A recent study has investigated when it is during the fixation that visual information is being attended (Blanchard, McConkie, Zola, & Wolverton, Note 8). For example, it may be that only the early part of the fixation is used for seeing the visual pattern, and that the remainder of the fixation period is used for identifying the meaning of the word or words seen during that fixation (Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981). This question is being studied by changing letters in the text part way through the fixation, so a particular word is different during the latter part of each fixation than it was during the earlier part. When the reader reports which word he saw in the text, this indicates whether a specific letter was being seen in the early or late part of the fixation.

The results clearly indicate that readers see words at different times during fixations, not always just at the beginning. Sometimes they report seeing the word that was present early in the fixation, and sometimes they can only report

the word that was present later in the fixation. Thus, it appears that readers attend to different things at different times during the fixation, and that attending to the letters, or the words of which they are part, can occur at various times. In fact, it seems quite possible that part of the process of developing reading skill is learning to attend to the text in an efficient manner from moment to moment. But this must be a topic for future research.

The point to be made from these findings is that, although the eyes may be still during a fixation, the mind is actively attending to the text in some sequence not presently known. This attention to visual details takes place even when the words are so highly constrained that the reader could guess them if he were asked to do so.

Integrating Information Across Fixations

In reading, as in other visual tasks, the person makes several fixations per second, each providing a slightly different view of the stimulus. Although these fixations are discreet, the reader has no experience of discontinuity from one fixation to the next. In fact, there is a feeling of a smooth flow through the text; the reader is not only unable to report the number of fixations he has made, he is even unaware that such a process is

taking place. This raises the question of how information from successive fixations is being brought together and integrated into a single flowing experience.

A common proposal has been that the person builds, in his mind, a single unitary visual image of the page, with each successive fixation simply adding more visual detail to it. Thus, the experience is said to be based on this mental image, which maintains continuity across fixations and assimilates detail from successive fixations, rather than on the individual fixations themselves. If this were the case, we would then think of the reader as reading from this mental image, rather than directly from the text itself. It should be noted that this view conflicts with the earlier-reported evidence suggesting that letters are typically seen only within a narrow region.

In order to test the possibility that an integrated visual image exists, people were asked to read text printed in AlTeRnAtInG cAsE, where every other letter was capitalized (McConkie & Zola, 1979). Skilled readers are able to do this with very little difficulty after practicing for a short time. Then, as they were reading from the CRT, during certain eye movements the shape of every letter was changed. Every upper-case letter was replaced by its corresponding lower-case form,

and vice versa, as shown in Figure 7. We reasoned that if the images from the two successive fixations were being brought together into a single mental image, they would now not fit together properly, and this would cause considerable difficulty to the reader. However, in conducting the study, we found that, not only did this manipulation not cause any difficulty, the readers were actually unaware that anything had changed and their eye movement records showed no indication of difficulty. Although the shape of every word and every letter was different on one fixation than it had been on the prior one, they had no awareness that any change had occurred. Thus, it appears that there must not be any integrated visual image of the text in the reader's mind. Rather, any information carried over from one fixation to the next must be some encoding which does not distinguish between whether individual letters were in upper-case or lower-case form. Apparently during the short period of the fixation, the word and letter information gives rise to some higher level of code, and the visual images are not preserved. The nature of this code must now be explored, as well as how one develops the ability to carry out this encoding in a rapid and automatic fashion (LaBerge & Samuels, 1974). This, also, must be a key in understanding the development of perception which occurs in learning to read fluently.

Insert Figure 7 about here.

Summary

Recent research leads to a view of the reader as being actively engaged in attending to the text in response to the needs of the comprehension processes. The task is to comprehend the message; the goal of the perceptual system is to provide the visual information needed to keep this mental activity moving smoothly. Apparently this comprehension process proceeds on a word-by-word basis, with the individual words being perceived and having their effect on the mind. This perception is occurring as it is needed, not just at the beginnings of fixations, and the visual information available for it to occur is that which is presently available from the retina, not that which is aggregated across a series of prior fixations. How long the eyes remain in a location, and how far they move next, are determined by the needs of comprehension processes, and the control of the eyes appears to be both quite precise and delicate.

Small differences in the text, or changes in the stimulus pattern, have effects on the perceptual or higher processing activities which are then reflected in small, but detectable, differences in the eye movement pattern.

Using Eye Movements to Study Other Aspects of Reading

We turn now from studies of perception to a consideration of how eye movement data might be used in the study of other aspects of reading. If the mind is directing the eyes in response to the needs of the higher mental processes, then it seems reasonable that the eye movement pattern should reveal certain aspects of those processes. This has been a very appealing notion to researchers investigating the cognitive processes, partly because there are so few other external indicators by which it is possible to observe what the mind is doing during cognition. It has also attracted the attention of those who wish to diagnose reading difficulties. Even a cursory comparison of the eye movement data of a very good versus relatively poor reader shows striking differences, with the poor reader typically showing shorter forward saccades, many more regressions, and a generally more erratic-looking pattern. While such data may be used to distinguish better from poorer readers (Taylor, Note 9), there is presently no good evidence that it provides a better indicator of

reading ability than do the commonly-used standardized tests. The problem is that, while the differences in eye movement patterns are obvious, it is not clear what these differences mean, other than that some people read more fluently than others. There are certainly instances in which problems of the visual or oculomotor systems can be detected through eye movement data (Pavlidis, 1981; Zangwill & Blakemore, 1972). But in most cases of reading difficulties, these are not the problems. The problem lies in the ability to properly identify the words and interpret the meaning encoded in the word sequences.

There was a period in the history of reading research when it was thought that poor eye movement patterns might be causing reading problems; that is, if people were taught to move their eyes like good readers do, they would be good (or at least better) readers. Attempts to do such training were sometimes successful in improving the eye movement pattern, but improved reading did not seem to be the result (Gibson & Levin, 1975). The view that is commonly accepted today is that while erratic eye movement patterns may be a symptom of reading difficulty, attempting to deal directly with this symptom is unlikely to have any beneficial effects for most people.

This is not to say, however, that eye movement patterns

cannot be useful for diagnosis. Indeed, it still seems quite likely that they can be a rich source of information about characteristics of a person's reading. However, to realize this potential first requires an understanding of the relationship between the higher mental processes and the control of the eyes during reading. The research investigating perception during reading, described earlier, begins to lay the groundwork for this understanding. However, much research is yet needed before we will have a deep enough understanding of this relationship to be able to do detailed diagnosis of comprehension difficulties from individual eye movement records.

Measuring the Time Needed to Process Different Aspects of Language

One major attempt has been made to use eye movement data as a measure of the time required to carry out various mental processes involved in the act of reading (Just & Carpenter, 1980). It was assumed that the time spent fixating a word corresponded exactly to the time required to process it. Thus, an average processing time for each word was calculated by finding the average amount of time a group of readers spent fixating it as they read the passage. Each word was then classified by its length, frequency in the language, function in

the language, etc. Regression analysis techniques were then used to find how much processing time was required by words of different lengths, of different frequencies, and of different functions. Some of the assumptions made in producing the processing time measure are probably faulty (Hogaboam & McConkie, 1981; Kliegl, Olson, & Davidson, Note 10). For instance, it is frequently the case that a word other than just the one fixated is being processed during a fixation (Hogaboam, Note 11), characteristics of a word can be seen on fixations on other words (Underwood & McConkie, Note 4; Kliegl, Olson, & Davidson, Note 10), and it is probably inappropriate to simply sum the time on a word resulting from multiple fixations on it (Kliegl, Olson, & Davidson, Note 10). While these problems make it likely that the actual processing times obtained in the study are not accurate, the general approach has considerable promise. Once there is a better understanding of exactly how to derive a measure of processing time for different segments of language from the eye movement data of people reading it, it may be possible to determine the relative amount of difficulty which different language constructions cause readers, and to compare different groups of readers in what produces difficulties for them.

Diagnosing Sources of Reading Difficulty

The development of techniques to study the perceptual processes occurring during reading, as people are actually engaged in reading a passage, has been an important step in reading research. The extension of these techniques to the study of language processing, now being attempted, is an important further development. In these studies, eye movement information has played a central role, both as a basis for making experimental manipulations (changing the text in specific ways as the person is reading it), and as a source of data which indicate whether stimulus changes or language characteristics are creating difficulty for the reader. This raises the question of whether these same techniques might be useful for diagnostic purposes.

The most noteworthy characteristic of these eye movement based research techniques is that they have been successful in providing rather precise information about specific aspects of perceptual and language processes in reading. That makes it likely that they will be very useful for diagnosis. Once a groundwork of research has been laid concerning the normal course of development in learning to read, it is likely that these techniques can be used to identify, rather precisely, whether a person is showing normal development in specific ways. Thus,

they will allow a reading specialist to test whether various aspects of a child's reading behavior are developing normally, and to detect deviations from a normal pattern. This will take place by having the student read a few carefully prepared passages, with specific language characteristics built into them, and perhaps with certain changes taking place in the text during the reading, while his eye movements are being monitored. After the reading, the eye movement records will be analyzed, and precise conclusions can be made about specific aspects of that child's perceptual and language processing. For instance, the data may indicate whether or not more time was taken at the point in the text where an inference is required for comprehension, or from what visual region words are being identified, or whether an entire word is perceived during a single fixation or is assembled from sub-word units acquired on successive fixations, or how attention is being deployed during fixations. Such information can then be of use to the remedial teacher in suggesting courses of action which might help the student overcome obstacles that are holding back the development of reading skill. This might be done in much the same way that a good violin teacher can help a student overcome limitations by changing hand or bowing arm positions that are limiting his progress. Knowing very specific facts about how the child is processing the text, either

perceptually or for language characteristics, is likely to provide the basis for selecting exercises that will help him change his approach in just the manner needed. The development of such diagnostic systems must await further research on reading development and disorders, but is likely to come into existence at some time in the not-too-distant future.

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Figure Captions

Figure 1. An example of the scleral reflection technique for monitoring eye movements. The center cylinder illuminates the eye with infrared light, and the two side cylinders are photosensors which respond to infrared light reflected from the surface of the eye indicated by dotted lines. If the eye moves to the left, the light level drops at the left photosensor because more of the iris moves into its field of view, while the light level at the right photosensor increases because more of the sclera moves into its field of view. Changes in these intensities indicate relative eye position.

Figure 2. An example of .8 second of raw eye movement data (horizontal movement component only). Time is represented along the X axis, and eye position along the Y axis. Points are plotted indicating the eye's position at each msec. When the curve is flat (as at A), the eyes are in a fixation. Movement of the eyes rightward is reflected in an upward movement of the curve (as at B), and movement of the eyes leftward is reflected in a downward movement of the curve (as at E). The location of each fixation on the line of text is represented by a dot over the corresponding letter position on the Y axis.

Figure 3. An example of an eye movement record showing where one reader fixated in reading a line of text. Each fixation is indicated by a digit under the line of text, with the digits indicating the order of the fixations. The number under each digit indicates the number of msec. which the eyes stayed at that location.

Figure 4. Nature of the change in the text that was used in the text-shift study. The location of one fixation is indicated on the first line by A under the line. During the following saccade, the text was shifted 2 letter positions to the right, as shown in Line 2. The following fixation, which normally would have been at the location marked by B in Line 1 was thus misplaced to the location marked by C in Line 2.

Figure 5. Appearance of the text during each of several fixations in the Underwood and McConkie (Note 4) study. On certain fixations, all letters more than a certain distance to left and right of the fixated letter were replaced with other letters, as seen on the lines indicating the appearance of the text on fixations 4, 6 & 8. Fixation location is indicated on each line.

Figure 6. Appearance of the text during each of several fixations in the McConkie (Note 5) study. During each eye movement, one of the letters changed, causing one word to be

different from one fixation to the next. Fixation location is indicated on each line.

Figure 7. Appearance of the text during two successive fixations in the McConkie & Zola (1979) study. The text was printed in alternating case. During the saccade from fixation 1 (shown on Line 1) to fixation 2 (shown on Line 2), the case of each letter was changed.

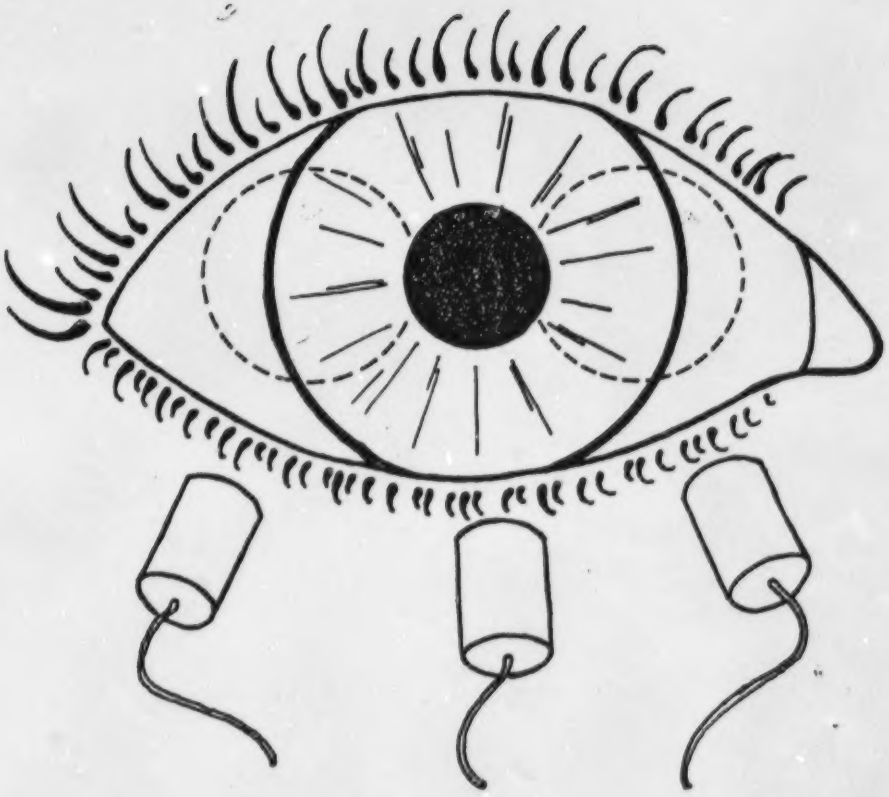
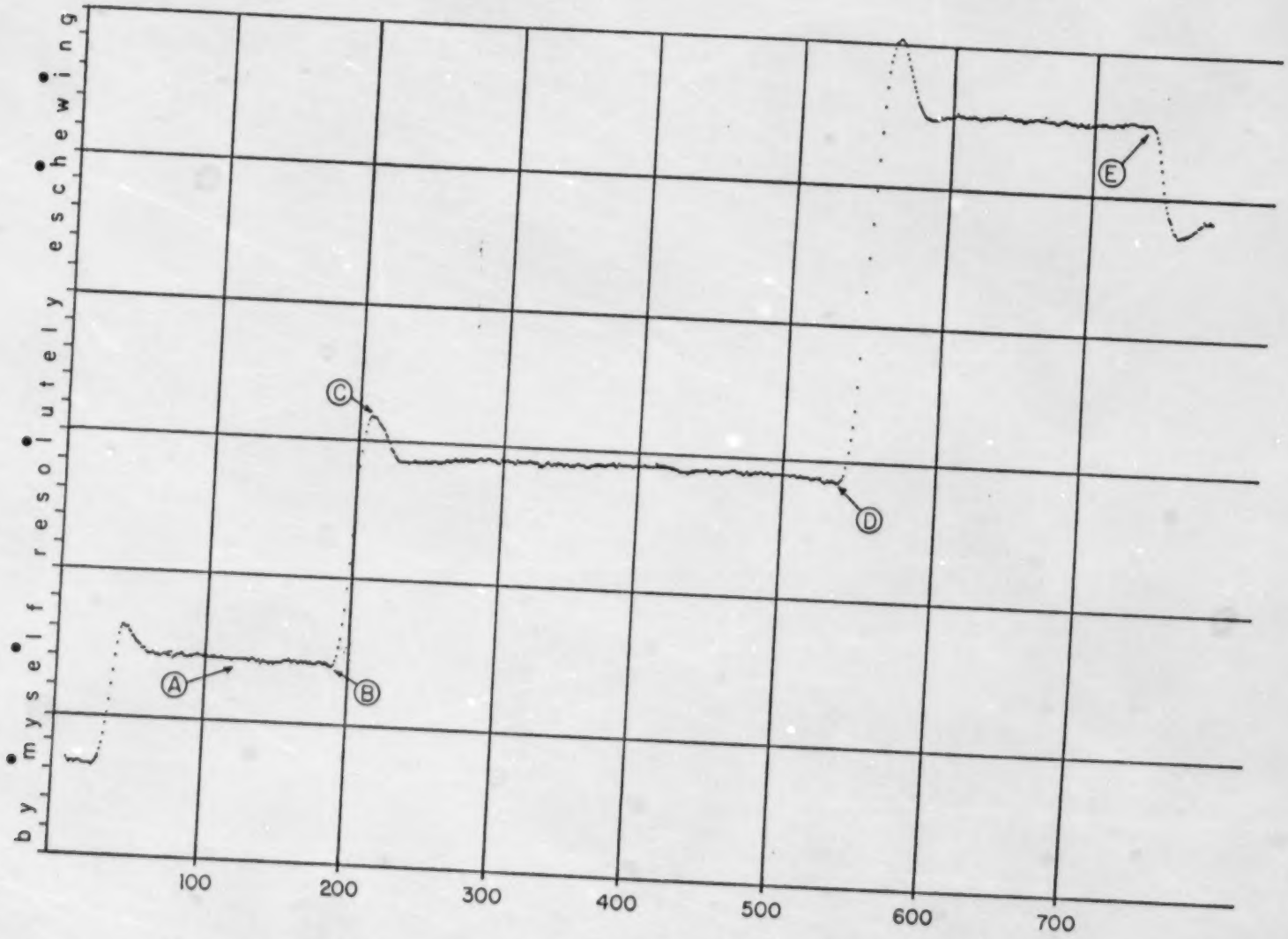


Figure 2


EYE POSITION
by myself resolutely eschewing
A
B
C
D
E
100
200
300
400
500
600
700
TIME (msec)

North America were connected by land. In 1725, he commissioned Bering,
A B

North America were connected by land. In 1725, he commissioned Bering,
C

built a ship and set sail in 1728. They discovered Saint Lawrence
2 1 3 5 4 6 7 8 9 0 1
253 122 139 24 339 280 296 214 268 235 102

Fixation	Appearance of text
6	His friends became concerned over what they thought* were sighs of despair.
7	His friends became concerned over what they thought were* signs of despair.
8	His friends became concerned over what they thought were sighs* of despair.
9	His friends became concerned over what they thought were signs of despair.*

Fixation	Appearance of text
1	One night, a demanding customer returned Crum's fried potatoes to
2	One night, a demanding customer returned Crum's fried potatoes to
3	One night, a demanding customer returned Crum's fried potatoes to
4	Zen ebyfh, a tnamnding customes snhosent Jsoa'r isbnt juhmhunr hu
5	One night, a demanding customer returned Crum's fried potatoes to
6	Zen ebyfh, a tnametbey customer retusent Jsoa'r isbnt juhmhunr hu
7	One night, a demanding customer returned Crum's fried potatoes ot
8	Zen ebyfh, m tnametbey vorhuans snhosent Jsoa'r isbed potatoes tu

a DaNiSh SeA cApTaIn, To ExPlOrE tHe NoRtH pAcIfIc ReGiOn. BeRiNg AnD
1

A dAnIsH sEa CaPtAiN, tO eXpLoRe ThE nOrTh PaCiFiC rEgIoN. bErInG aNd
2